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INFRARED ASTRONOMY: A 20 YEAR PROJECTION

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PREFACE

This twenty year projection for infrared astronomy was prepared at the request of the NASA Goddard Space Flight Center to aid in a projection of its scientific goals for the coming years. The report discusses reasons for the importance of infrared astronomy, the instrumentation needed to make significant observations, and the role of ground-based and space borne projects in a comprehensive infrared program. It indicates the areas in which technical advances are most urgently required and suggests a possible time scale for instrument development and utilization. After the report had been prepared, the authors became aware that there might be considerable general interest in the document, particularly on the part of other workers in the field. We hope that discussions will arise from this statement of our personal position which may lead to a consensus concerning large instruments and programs requiring extensive government support.

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I REASONS FOR THE IMPORTANCE OF INFRARED ASTRONOMY

Infrared observations are an important ingredient of our understanding of fundamental astronomical processes. These processes may be thought of as the initial formation of astronomical systems, the production of energy in some objects, the degradation of radiation falling on others, and the final dispersal or contraction of the systems.

A THE DISCOVERY OF OBJECTS BY INFRARED OBSERVATIONS

In the first place, one is of course interested in the existence of astronomical objects. Not all such objects are detectable by their emission or absorption of visible radiation. For example, a large infrared radiating object has recently been found in the Orion nebula for which no visible counterpart has been detected. One can infer that this object is a star or star cluster in the process of formation. In another case, a young star, R Monocerotis, appears to be surrounded by an infrared emitting dust cloud that could well be a system of planets in the process of formation. All astronomical objects are believed to begin with a condensation in a diffuse medium. Such condensing objects will generally be cool at first, emitting the bulk of their radiation in the infrared. Thus infrared observations allow one to trace objects back to their birth.

B ENERGY PRODUCTION AND RADIATION IN ASTRONOMICAL OBJECTS

One wishes to understand the mechanisms of energy production during the life of an object. It is the internal source of energy that distends objects such as stars; the rapid liberation of this energy that sometimes explodes stars; and the failing of the source of energy that lets the star finally collapse to a fate determined by the residual mass. The radiation liberated in the infrared may be a significant fraction of the total. For example, the brightest quasar 3C273 appears to be radiating about 90% of its total emission in the infrared.

C DEGRADATION OF ENERGY INTO THE INFRARED

One wishes to understand the processes which occur in dissipation of the energy radiated by objects, and its cooling, or degradation, into longer wavelength radiation through interaction with matter and also from the expansion of the universe. Also, one would like to know of the mechanisms that are driven by the absorption and reemission of this radiation. Finally, most of the cooled radiation from all objects will appear in the infrared for the following reasons. Objects will only be cooler than the cosmic background radiation temperature $3^{\circ}K$ in the extremely odd circumstance that they act as natural refrigerators. On the other hand, objects known from visual studies are hotter than $3000^{\circ}K$ emitting most of their radiation in the visible or near ultraviolet. The cooled energy from these objects should mainly appear between the long wavelength limit of the visible spectrum and the black body maximum for $3^{\circ}K$, at 1 mm. This is the extent of the infrared spectrum. One such cooling process is the re-radiation of starlight by interstellar dust. A substantial part of the total radiation of a galaxy should appear degraded into the infrared by these particles.

D DISSOLUTION OF OBJECTS AND ITS OBSERVATIONS IN THE INFRARED

The dissolution of objects is not easy to observe. However for more than a decade it has been known that red giant stars are ejecting much of their matter. It has been predicted by some astronomers that this ejected matter should contain solid particles that should be degrading the starlight and re-radiating it in the infrared. Thus this should provide one of the few ways of making quantitative observations of this ejected matter. In fact, flickering infrared emission from regions around red giant stars has already been reported, but the flickering is on such a short time scale that it cannot yet be simply related to the mass loss. This infrared observation has provided a new astronomical mystery to be solved in the future.

E DETERMINATION OF PHYSICAL PROPERTIES BY INFRARED SPECTROSCOPY

In all celestial objects the mechanism of the emission of radiation provides the clues that allow one to discover the nature of the object. Thermal radiation from opaque objects is often modified by gaseous absorption and allows one to employ spectroscopic means to determine temperature, pressure, chemical composition, and other surface properties. Furthermore, low resolution infrared spectroscopy can be used to distinguish those cases where the radiation is non thermal and depends in detail on the fundamental processes occuring in the system. The processes responsible for non thermal sources are not well understood. It is in the understanding of them that the astrophysicist hopes for the greatest advances. The infrared radiation from 3C273 is probably one case of non thermal emission. The flickering emission from the regions around the red giant stars is another. Recently non thermal emission has been found in the radio spectrum where OH molecules in some dense regions of interstellar space appear to be acting as natural masers. Such natural masers are also likely to occur in the infrared region of the spectrum where laboratory studies have shown molecular masers to be very easily produced. However, it is not known whether or not this scientific curiosity is of significance for the history of astronomical objects.

II INSTRUMENTATION

Infrared observations have been rare until the past five years because of technical difficulties. A) Infrared detectors cannot be made as sensitive as receivers in other spectral regions because of the strong thermal emission of all substances used to build the instruments. B) The earth's atmosphere is highly absorbing and emitting in the infrared. C) Few large telescopes have been available for infrared observations. D) Because of the limitations of detector sensitivity, high efficiency spectrographs are required for the infrared. These points are discussed below.

A DETECTORS

Infrared detectors are largely limited by the thermal radiation falling on them. The sensitivity can, however, be raised by cooling the detectors and letting them see the outside world only through narrow angular apertures and cooled narrow band filters. Although this technique is employed with considerable success, it cannot be carried to extreme. The narrow band and the small angular aperture also restrict the radiation coming from astronomical objects. Even point sources appear as surfaces because of diffraction. Thus the expected further improvement of detectors is likely to make only modest contributions to sensitivity in the region 4-100μ where thermal emission from the surroundings is greatest. In the further and nearer infrared however, significant detector advances may still be usefully made. Also for special problems such as the study of narrow spectral lines, some improvement seems likely. One cannot forsee the entire instrument of a large satellite telescope being cooled enough to appreciably modify these comments, at least not in the next 20 years.

Because of the sensitivity to thermal radiation, the cooling of the detector surroundings is vital. Present ground based and balloon borne infrared detectors operate near 1.8°K using liquid helium as a coolant. So far no means of reaching these or lower temperatures from a satellite for extended periods has been demonstrated. The sensitivity of detectors may empirically be estimated to vary as $1/T^2$, where T is the absolute temperature, while the observing time to attain a particular signal to noise ratio will vary as $1/T^4$. Under these circumstances, if one can attain for example only 20°K in a satellite, three months of satellite observations may be inferior to a single rocket flight where the helium coolant is at less than 2°K.

It is crucial that cooling systems capable of attaining temperatures in the range 2°K to 0.1°K be developed for satellite use. This one item should have highest priority of all instrument development in the next decade.

B ATMOSPHERIC ABSORPTION AND EMISSION IN THE INFRARED

The infrared divides into two spectral regions:

(i) 1000-25μ. This region is virtually inaccessible from the ground. All studies must be made from above most of the atmosphere. Water vapor is the main absorber. Partial transparency is expected from the highest aircraft altitudes (higher than 40,000 ft). Water vapor is rapidly frozen out of the atmosphere with increasing altitude, and probably heights of 50,000 ft. and higher will be needed to make consistently good observations. From balloons, only a few percent of residual absorption is left, but if water vapor exists in stratospheric clouds, balloon and aircraft observations will be severely limited, and rockets and satellites would be needed. Some slight indications in favor of a clear stratosphere were obtained from a balloon sky survey at 300 μ, carried out by the Institute for Space Studies, but further observations at wavelengths where water absorbs more may change this tentative conclusion.

(ii) 25 μ - 1 μ. This region is partially accessible from the ground. Major absorbers are water vapor and carbon dioxide. Studies from aloft will be needed to search for objects with a low surface brightness, and to search for spectral features that coincide with terrestial atmospheric absorption bands. Here one should note that CO_2 does not freeze out of the atmosphere, and studies of CO_2 bands in the spectra of other planets may need to be made from rockets or satellites.

C THE AVAILABILITY OF LARGE TELESCOPES FOR INFRARED OBSERVATIONS

Large telescopes are important for studying objects of small angular diameters and for studying the structure of extended objects. Telescopes of a few centimeters aperature are adequate for photometry of the Milky Way, the Zodiacial light, and other objects of few degrees extent. Telescopes of a meter aperture are suitable for photometry of planets, emission nebulae and the brightest point sources. A three meter telescope could be used for structural and spectroscopic study of these objects and for fainter point sources.

Telescopes in all those sizes would be useful both on the ground and in satellites. The surface quality for a ground telescope need give an image of only about 2 seconds of arc which is the spreading of a stellar image by fluctuations in atmospheric refraction. At the present time telescopes of this quality can be constructed with apertures up to at least 3 meters diameter at moderate cost. Larger telescopes would be useful even if cost limitations required compromising the image quality to as poor as 1 minute of arc for a 25 meter telescope. Such a telescope would be useful for high resolution infrared spectroscopy of relatively bright sources such as planets and the new object discovered in the Orion nebula at 20 μ . The desired surface quality of satellite telescopes will be determined by the diffraction image of a point source. For example at 50 μ this would be 4 seconds of arc for a 3 meter telescope.

Despite the moderate cost, some care should be given to placing the largest of the ground telescopes in the most favorable driest sites such as certain mountain sites in the South West and in Hawaii. At present the best U.S. site is suspected to be in Hawaii. One might consider establishing a national infrared facility there if surveys confirm this belief.

Aloft one can forsee uses for telescopes of the following sizes, each associated with a particular pointing accuracy.

(i) Less than 30 cm aperture pointed to $\pm$ 6 minutes of arc or worse. These would be used for studying extended objects.

(ii) Less than 1 meter pointed to $\pm$ 6 seconds of arc. For some specialized purposes these might need to be pointed to $\pm \frac{1}{2}$ second of arc. These would be used for studying the brightest point sources.

(iii) Telescopes larger than 1 meter will be needed for studying faint point sources and for obtaining spectral information from the brighter sources such as planets. For faint sources the pointing accuracy must be high, approximately $\pm$ 1 second of arc, and the surface must be fairly good, accurate to about $\pm$ 5 wavelengths of visible light. For spectroscopic studies of bright sources, the accuracy required is not as high. Thinking in terms of Apollo hardware, one might hope for 3 meter telescopes of these kinds. It has been suggested that a single high precision multi-purpose telescope should be built with its properties optimised for visual and ultraviolet work. Unfortunately, it seems highly unlikely that such a telescope would be useful for the infrared because of the vast thermal emission that would be expected from a telescope not primarly designed for minimum number of surfaces and reflection coated specifically for infrared use above the atmosphere. One might well find that if separate infrared 3 meter telescopes could not be made available, progress might best result from perfecting 1 meter sized infrared instruments.

D SPECTROGRAPHS AND SPECTROMETERS

The most efficient way of obtaining infrared spectra is with multiplex spectrometers. In these systems many spectral channels are simultaneously observed on one detector element by using various modulation techniques. If the source is extended, the high throughput (area x solid angle) such as occurs with a Michelson interferometer provides a further gain in efficiency. Such systems are most advantageous for high resolution spectral studies. Low resolution studies or studies involving few spectral elements may well be best made with tuneable filters or scanning monochromators. Unfortunately the multiplex instrument is far more sensitive to external conditions, such as source variations or motion of the image in the entrance aperature. Therefore the choice of instrument will always depend on the exact nature of the astronomical problem, and the possibility of extremely accurate guiding of the telescope. Laser spectrographs may eventually become available for certain specialized problems, for example studies of interstellar emission lines, but their use appears to be about 10 years off. It seems highly unlikely that the Laser superhetrodyne receiver will become an important astronomical tool in the period up to 1987.

III THE ROLE OF GROUND BASED AND SPACE BORNE PROJECTS IN THE INFRARED PROGRAM

The different locations for a detector and telescope each have their own advantages, summarised below.

A GROUND BASED PROJECTS

These can have advantages of low cost and simplicity, short lead time for experiments, and ease in using for graduate student training, particularly crucial in this area in which so few people are at present working. The disadvantages are that even from the driest high altitude sites, for example Arizona or Hawaii mountain tops , severe atmospheric attenuation and emission is expected. However valuable new results may be obtained with:

(i) Moderate resolution (~ 2-4 second of arc) large telescopes (~ 3 meter) for searching for and studying faint objects.

(ii) Low resolution (~ 1 minute of arc) giant telescopes (up to 25 meters) for obtaining high spectral resolution of the brightest objects. Both of these can be low cost systems.

B AIRCRAFT FLIGHTS

The advantage of the airplane is the ease of modifying the equipment and flying again. The highest altitudes available are needed because of the rapid fall off in water vapor with height in this region of the atmosphere. Commercial and military planes capable of altitudes above 50,000 feet exist. However planes such as the Convair 990 from which some infrared observations are planned seem useful for observations short of 25μ but probably inadequate for most longer wavelength observations. A smaller high altitude plane for developing infrared instrumentation and making observations with telescopes up to about 10 inch aperture is needed.

C BALLOON FLIGHTS

For the simplest observations that require little or no human intervention balloons should continue to be used throughout the next 20 years. However infrared work should not require the development of highly sophisticated vehicles whose repair time and costs are very large. For initial sky survey work, balloons should prove very valuable. The subsequent use of balloons will continue to play an important role where the altitude is not a limitation and the short lead time over satellite experiments is an advantage.

D ROCKET FLIGHTS

The disadvantage of a short observing time must tell against rockets in the long run. However during the next 5 years, there may be useful survey results, particularly if the atmosphere at balloon altitudes proves to be more cloudy than hoped at present. The absolute measurement of dark sky brightness at various wavelengths will initially be tried from rockets. This extremely difficult task may spread into the period 1972-1987.

E SATELLITE PROJECTS

The value of satellites for infrared observations will depend on the availability of detector cooling systems of adequately long lifetime. If work were started on such systems now, a vehicle with a telescope of 1 meter in diameter might be launched in ther period 1972-1975. A 3 meter telescope should also go into design when the cooling system has been perfected to the point where its form is known. The expense of large telescopes would be such that their instrumentation should be modifiable by man in orbit. However there seems to be little need for man in the day to day operation of such systems. The major expenses of such telescopes would occur from 1972 onward.

F LUNAR AND PLANETARY MISSIONS AND FLYBYS

Infrared spectroscopy will be important as a remote sensing tool. Most fly-bys in the period up to 1987 should have infrared spectrographic equipment. The precise equipment will depending on the state of ones existing knowledge of the planet, and on the ability to cool the detector. This will provide a useful technique for analysis planetary atmospheres. However for solar system objects without an atmosphere initial studies from the ground of the moon in the mid infrared suggest that this is not a powerful tool for studying surface composition.

IV CONCLUSIONS

The most urgent need in infrared astronomy is for a cooling device to give extremely low temperatures between 0.1 and 2°K in a satellite environment. All infrared satellite and fly-by work will depend on this development.

While ground based work is sometimes not considered to be a part of space exploration, the sensible and economical scientific use of post Apollo satellite systems requires an adequate supporting ground observation program and cannot be discussed without it. Ground studies will continue to be extremely important in making discoveries, and in indicating the areas of greatest importance for the more expensive flight programs. The needs are adequate support for instrument development (detectors, spectrographs) and for the creation of a few large and very large moderate quality telescopes to be placed on dry mountain sites. Further surveys to determine the location of minimum humidity sites would be extremely valuable. For example at a recent infrared conference Professor Salmonovich reported that the cold pole in Siberia turns out to be an observing site far inferior to expectations. No adequate explanation of this exists.

An infrared research airplane is needed for altitudes of 50,000 feet or higher. Some existing commercial and military planes appear to be adequate.

Rocket and balloon work should be supported with the expectation that its most useful period will be in the forthcoming 5 years (1967-1972). This statement assumes that as this balloon and rocket work is phased out it will be replaced by infrared post Apollo satellite systems. Balloon instruments should in general be simple and inexpensive. A modest level of balloon flights should be continued indefinitely for studies in new areas.

Survey work should be the main astronomical goal of the next five years. The following 15 years should be a period of consolidation and gathering more detail along lines suggested in the opening section of this report. This work will require the use of 1 meter and later 3 meter telescopes in orbit.